function of wavelength. IPCE is obtained by the following equation:

$$\mathrm{IPCE}[\%] = \frac{1240[\mathrm{eV \cdot nm}] \times J_{\mathrm{SC}}[\mu\mathrm{A\,cm^{-2}}]}{\lambda[\mathrm{nm}] \times \Phi[\mu\mathrm{W\,cm^{-2}}]} \times 100 \tag{15.1}$$

where J_{SC} is the short-circuit photocurrent density for monochromatic irradiation, λ is the wavelength, and Φ is the monochromatic light intensity. As shown in Figure 15.7, solar cells sensitized by the Ru complex photosensitizers can efficiently convert visible light to current. N3 dye ($RuL_2(NCS)_2$) responds to light from 400 to 800 nm, and black dye ($RuL'(NCS)_3$) responds to the near-IR region up to 950 nm. The IPCE of the N3 dye-sensitized solar cell reaches 80% at 550 nm and exceeds 70% in the region from 400 to 650 nm. Taking into consideration losses due to light reflection and absorption by the TCO substrate, the internal photon-to-current conversion efficiency is effectively 90 to 100%, indicating high performance of the DSSC. IPCE is also given by the following equation:

$$\mathrm{IPCE} = \mathrm{LHE}\ \phi_{\mathrm{inj}}\eta_{\mathrm{c}} \tag{15.2}$$

$$\mathrm{LHE} = 1 - T = 1 - 10^{-A} \tag{15.3}$$

where LHE is the light-harvesting efficiency, ϕ_{inj} is the quantum yield of electron injection, and η_c is the efficiency of collecting the injected electrons at the back contact. According to equation (15.2), if ϕ_{inj} and η_c are almost equal to unity, IPCE is determined by the LHE (i.e. $1 - T$) of the dye adsorbed on the film (shown in Figure 15.4).

Solar energy–to–electricity conversion efficiency, η, under white light irradiation (e.g. AM1.5) can be obtained by the following equation:

$$\eta = J_{\mathrm{SC}} \times V_{\mathrm{OC}} \times \mathit{ff}/I_0 \times 100 \tag{15.4}$$

where I_0 is the photon flux (approximately 100 $\mathrm{mW\,cm^{-2}}$ for AM1.5). A current versus voltage curve obtained for a nanocrystalline TiO_2 solar cell sensitized by black dye is shown in Figure 15.8. Evaluation of the performance was carried out at the National Renewable Energy Laboratory (NREL) operated by the US Department of Energy. An efficiency of 10.4% was obtained (cell size = 0.186 $\mathrm{cm^2}$, J_{SC} = 20.53 $\mathrm{mA\,cm^{-2}}$, V_{OC} = 0.721 V, and ff = 0.704) [8, 18].

15.1.4 Charge-transfer Kinetics

15.1.4.1 Electron injection process

Recently, the electron-transfer kinetics in the DSSC, shown as a schematic diagram in Figure 15.9, have been under intensive investigation. Time-resolved laser spectroscopy measurements are used to study one of the most important primary processes, electron injection from photosensitizers into the conduction band of semiconductors [28–47]. The electron-transfer rate from the photosensitizer into the semiconductor depends largely on the configuration of the adsorbed photosensitizer material on the semiconductor surface and the energy gap between the LUMO level of the photosensitizer and the conduction-band